Fermilab FERMILAB-Pub-00/190-A August 2000

The Distribution of [OII] Emission-line Widths of LCRS Galaxies

Michael Blanton

NASA/Fermilab Astrophysics Center
Fermi National Accelerator Laboratory, Batavia, IL 60510-0500;
blanton@fnal.gov

and

Huan Lin[1]

Steward Observatory, University of Arizona,
933 N. Cherry Ave., Tucson, AZ 85721;
hlin@as.arizona.edu

ABSTRACT

We present a simple functional form for the joint distribution of R-band luminosity and [OII] 3727 emission-line equivalent widths of galaxies, and show that this form is a good fit to the galaxies in the Las Campanas Redshift Survey. We find a relationship between [OII] equivalent width W and R-band luminosity L_R of the approximate form: $\langle W\rangle \approx (10\text{Å})(L_R/L_{R,*})^{-1/2}$, where $L_{R,*}$ is the characteristic luminosity in the Schechter function. Because this joint distribution yields information about the relationship between stellar mass in a galaxy and its recent star-formation rate, it can be useful for testing theories of galaxy formation. Furthermore, understanding this joint distribution locally will make it easier to interpret the evolution of [OII] emission-line widths to higher redshifts.

1. Motivation

Modern redshift surveys such as the Las Campanas Redshift Survey (LCRS; Shectman *et al.* 1996) have large, homogeneous sets of spectra from which one can measure star-formation indicators such as the [OII] 3727 Å forbidden line. It is known that the luminosity function of galaxies is dependent on the emission-line properties of the galaxies under consideration (Lin *et al.* 1996; Cowie *et al.* 1996; Ellis, *et al.* 1996; Small *et al.* 1997) but the detailed relationship between these emission-line properties and galaxy luminosity has not been explored. Here we present a calculation of the joint distribution of R-band luminosity and the equivalent width of the [OII] 3727 line for LCRS galaxies, as well as an analytic form for this distribution which fits the data well. This joint distribution is a useful quantity to compare with the predictions of galaxy formation models (*e.g.*, Cen & Ostriker 1998, Pearce *et al.* 1999, Somerville *et al.* 1999, Kauffmann *et al.* 1999).

While the LCRS is the largest completed redshift survey to date, there are at least three drawbacks to the sample to be kept in mind. First, the survey is R-band selected and limited by central surface brightness; thus, the latest type galaxies, which typically have the strongest emission lines, are preferentially excluded from the survey, potentially biasing our results. Second, the fits to the equivalent widths of the emission

[1]Hubble Fellow

lines fail for some galaxies, because their spectra do not have sufficient signal-to-noise to measure the line. It is likely that the failure rate of the fit depends on the true equivalent width of the line, and this unknown incompleteness is a potential worry. On the other hand, we show below that our results are robust to the lower limit of equivalent widths we consider. Given the typical equivalent width errors of $2\AA$, our results are most appropriate for galaxies with equivalent widths $> 4\AA$, to which we limit our sample. Redshift surveys underway, such as the Sloan Digital Sky Survey (SDSS; York, *et al.* 2000) and the Two-degree Field Galaxy Redshift Survey (2dFGRS; Colless 1998), will be able to overcome these two difficulties. A final problem, noted by Kochanek, Pahre, & Falco (2000), is that the spectra are taken using fibers with a diameter of $\sim 3''$, which for typical distances of galaxies in the sample is about 4 h^{-1} kpc. This may cause an "aperture bias" which underestimates the equivalent width of emission lines at low redshift because the fiber probes the inner, bulge component of spirals, rather than their disks, which contain the bulk of the star-formation. The SDSS may be able to constrain this effect by examining the four optical colors which the survey will measure, and comparing the colors within fiber-sized apertures to the global colors of each galaxy.

This paper is organized as follows. Section 2 briefly describes our method for calculating the joint luminosity and equivalent width function, and presents a simple fitting function based on that of Schechter (1976). Section 3 describes the results using LCRS R-band luminosities and equivalent widths of [OII] 3727 measured by Lin *et al.* (1996). Section 4 suggests directions of future research.

2. Joint Distribution of Luminosity and Equivalent Width

We follow Sandage, Tammann, & Yahil (1979) and Efstathiou, Ellis, & Peterson (1988), maximizing the conditional probability that each galaxy j, given its redshift z_j, has its measured luminosity L_j and equivalent width W_j:

$$
\begin{aligned}
p(L_j, W_j | z_j) &= \frac{p(L_j, W_j, z_j)}{p(z_j)} \\
&= \frac{\Phi(L_j, W_j) f_g(m_j)}{\int_{L_{\min(z_j)}}^{L_{\max(z_j)}} dL \int_{W_{\min}}^{W_{\max}} dW\, \Phi(L, W) f_g(m)},
\end{aligned}
\tag{1}
$$

Here $L_{\min(z_j)}$ and $L_{\max(z_j)}$ are the minimum and maximum luminosities observable at redshift z_j, given the flux limits of the field which contains galaxy j. $W_{\min}$ and $W_{\max}$ are the minimum and maximum values of the equivalent widths of our sample. (Lin *et al.* 1996 find the minimum observable equivalent width to be approximately constant with redshift). $f_g(m)$ represents the magnitude dependence of the redshift completeness. The likelihood of a given model for $\Phi(L, W)$ is given by the product of this conditional probability over all galaxies in the sample. Since this conditional likelihood is independent of density, the normalization must be calculated separately. We use the simple estimator:

$$
n_1 = \frac{1}{V} \sum_{j=1}^{N_{\rm gals}} \frac{1}{\phi(z_j)}, \tag{2}
$$

where V is the size of the volume probed, and $\phi(z)$ is the selection function:

$$
\phi(z) = \int_{L_{\min}(z)}^{L_{\max}(z)} dL \int_{W_{\min}}^{W_{\max}} dW\; \Phi(L, W) f_g(m) f_t. \tag{3}
$$

f_t is the local sampling fraction.[2] Lin *et al.* (1996) find for the luminosity function that this estimator yields similar results to the minimum variance estimator of Davis & Huchra (1982) for this sample.

We use two models to describe $\Phi(L, W)$. First, we use the non-parametric form described by Efstathiou, Ellis, & Peterson (1988), whose extension to the two dimensional plane of L and W is trivial. Essentially, this method divides the (L, W) plane into bins of equal logarithmic width, and assumes the distribution within each bin is constant. A fast iterative method can then find the set of values which maximize the likelihood, and we can estimate the errors by evaluating the second derivatives of the likelihood function at the fitted values.

Second, following Sandage, Tammann, & Yahil (1979), we find the maximum likelihood fit to a parametrized function. To do so, we parametrize the joint function as a modified Schechter function, which is motivated by the results below:

$$\Phi(L, W) dL dW = \phi_* \left(\frac{L}{L_*}\right)^{\alpha} \exp\left(-L/L_*\right) \Psi(W|L) dW \frac{dL}{L_*} \tag{4}$$

where the conditional equivalent width function is:

$$\Psi(W|L) dW = \frac{1}{\sqrt{2\pi}\sigma_W} \frac{dW}{W} \exp\left[-\frac{1}{2\sigma_W^2}\left(\ln\frac{W}{W_0} - A\ln\frac{L}{L_*} + \frac{\sigma_W^2}{2}\right)^2\right] \tag{5}$$

That is, at each luminosity, the equivalent widths are distributed log-normally about a mean value which can be expressed as a function of luminosity as:

$$\langle W\rangle = W_0 \left(\frac{L}{L_*}\right)^{A}. \tag{6}$$

σ_W parametrizes the width of the log-normal distribution. We use this function, and maximize the likelihood in Equation (1) over the five parameters L_*, α, W_0, σ_W, and A.

For the parametric fit, we calculate the error bars using 200 Monte Carlo realizations. For each realization, we take the redshifts of all the galaxies in the actual LCRS sample to be the redshifts for the "galaxies" in our realization. Then, we select a luminosity and [OII] equivalent width for each galaxy using Equation (4), limiting the range of absolute luminosities for each galaxy to that which is within the flux limits at that redshift. Then we maximize the likelihood for this realization. This procedure allows us to examine the distribution of the parameters over all the realizations, and thus calculate the error bars, and to determine whether our method is biased. We are also able to directly compare the likelihood values for the realization to the likelihood value of the data sample. If the fit is consistent with the data, these likelihoods should be comparable; if the fit is not consistent, the likelihood value for the data will always be smaller than that for the realizations.

We calculate distance moduli assuming an Einstein-de Sitter universe. We use K-corrections of the form $K(z) = 2.5\log_{10}(1+z)$ (Lin *et al.* 1996). Throughout, we assume $H_0 = 100\ h$ km/s/Mpc with $h = 1$; to convert to other values of h, the absolute magnitude scale is shifted by $5\log_{10} h$, and the luminosity function normalization by h^3. For plotting purposes we show the luminosity function expressed per unit logarithm $\hat{\Phi}(L, W) = n_1(\ln 10) L\Phi(L, W)$.

---

[2]For a fuller explanation of the meaning of the quantities f_g and f_t, consult Lin *et al.* (1996).

3. Results for the LCRS

Here we present the joint distribution of L_R and the equivalent width of [OII] 3727, for a sample of galaxies with $-22.5 < M_R < -16.5$ and $5,000$ km/s $< cz < 50,000$ km/s, selected from the North and South 112-fiber fields in the LCRS. The equivalent widths were measured by Lin *et al.* (1996), by fitting for the position, the width, and the amplitude of a Gaussian to the continuum-subtracted spectrum near the predicted location of [OII] based on the redshift. For about 25% of the objects, the spectra were too low signal-to-noise to constrain these parameters; the equivalent-width dependence of this incompleteness is unknown. The estimated errors in the measured equivalent widths are about $2\AA$ on average. To minimize the effects of incompleteness and errors, we include only measured equivalent widths $> 4\AA$ in our analysis, leaving about 8,500 galaxies in our sample.

Figure 1 shows the non-parametric fit as the thin solid lines with error bars. Each line shown represents a bin of equivalent widths, whose central value is given. Some of the lines are offset for clarity, as described in the caption. Note the characteristic difference between the strong emission line galaxies, which are in general less luminous and have a steeper faint-end slope, and the weak emission line galaxies, which are brighter with a shallower faint-end slope. This result accords qualitatively with that of Lin *et al.* (1996) and those of numerous other investigations of the dependence of the luminosity function on [OII] equivalent width (Cowie *et al.* 1996; Ellis, *et al.* 1996; Small *et al.* 1997) and on spectral type in general (Zucca *et al* 1997; Bromley *et al.* 1998; Folkes, *et al.* 1999; Loveday, Tresse, & Maddox 1999).

We also show the modified Schechter function fit in Figure 1 as the thick solid lines for each equivalent width shown (again, some are offset for clarity). Apparently this model does a pretty good job, though it uses 6 parameters: the ordinary Schechter parameters ϕ_*, L_*, α, plus the parameters describing the dependence of equivalent width on luminosity W_0, σ_W, and A (which is negative, because brighter galaxies have smaller equivalent widths). The best-fit values of these parameters are given in Table 1. Note that it is approximately true from these results that

$$\langle W \rangle \approx (10\AA) \left(\frac{L_R}{L_{R,*}}\right)^{-1/2}. \qquad (7)$$

Also, the Schechter parameters ϕ_*, L_* and α agree generally with the results of the independent analysis of Lin *et al.* (1996), although the faint end slope here is a bit steeper.

Table 1 also gives the errors in the modified Schechter parameters, as well as the correlation matrix between these parameters, determined from 200 Monte Carlo realizations, as described above. We have found that the bias in the maximum likelihood method is smaller than the error bars in this sample. Furthermore, we find that the fraction of Monte Carlo realizations which have likelihoods worse than that found for the data is about $P_{\mathrm{worse}} \approx 0.47$; this means that the likelihood for the data is comparable to the likelihoods from the Monte Carlo realizations, indicating that the fit is consistent with the data.

We have experimented with performing the modified Schechter function fit with limiting equivalent widths between $0.5\AA$ and $9.5\AA$, instead of the limiting value of $4\AA$ used for the results just presented. The parameters appear fairly robust to what this lower limit is. The largest changes are in the faint-end slope, which varies from $\alpha \sim -0.75$ at a limiting equivalent width of $0.5\AA$ to $\alpha \sim -1.1$ at a limiting equivalent width of $9.5\AA$; that we measure a slightly different faint-end slope than Lin *et al.* (1996) is thus related to our choice of a limiting equivalent width of $4\AA$. Meanwhile, M_* varies by about 0.15 magnitudes. However, the changes in the parameters which describe the distribution of equivalent widths are quite small. W_0 varies by $< 3\%$, σ_W varies from 0.85 to 0.75, and A varies from -0.45 to -0.49. This consistency simply tells us that the modified Schechter function is good at fitting the combination of the intrinsic equivalent width distribution and the incompleteness function. Nevertheless, we find it encouraging that the nearly same analytic form fits equally well the high equivalent width galaxies, which we are fairly confident of, and the low equivalent width galaxies, which may suffer from incompleteness as a function of equivalent width.

4. Discussion

We have presented a simple functional form which seems to describe well the joint distribution of luminosity and the equivalent width of the [OII] 3727 emission line in the LCRS. We caution that the dependence of completeness on equivalent width is unknown, and further, that we have not accounted for the distribution of the equivalent width errors (on average about $2\mathring{A}$) in our analysis. Upcoming surveys such as the SDSS and 2dFGRS will provide larger homogeneous sets of spectra with better resolution, and will overcome a number of the problems encountered here.

The joint distribution function $\Phi(L_R, W)$ can provide a useful tool for testing theories of galaxy formation, because the R-band luminosity is an approximate indication of the stellar mass contained in each galaxy and the equivalent width of [OII] 3727 is an approximate indication of recent star-formation in the galaxy. By combining hydrodynamic or semi-analytic models for galaxy formation, such as those mentioned above, with spectral synthesis models (Leitherer *et al.* 1996; Kennicutt 1998), it may be possible to place strong constraints on the properties of the star-formation history of galaxies. In this vein, understanding this joint distribution locally is also helpful in interpreting the evolution of [OII] emission at higher redshifts and thus the evolution of the star-formation rate of the universe (Hogg *et al.* 1998).

Thanks to Scott Dodelson, Daniel Eisenstein, David Hogg, Siang Peng Oh, Ravi Sheth, Doug Tucker, and Idit Zehavi for useful discussions. Thanks to Michael Strauss for extensive advice and comments. MB is grateful for the hospitality of the Department of Physics and Astronomy at the State University of New York at Stony Brook, who kindly provided computing facilities on his frequent visits there. MB acknowledges the support of the DOE and NASA grant NAG 5-7092 at Fermilab. HL acknowledges support provided by NASA through Hubble Fellowship grant #HF-01110.01-98A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS 5-26555. Finally, this work would not have been possible without the public availability of the Las Campanas Redshift Survey data, for which we thank the LCRS team.

REFERENCES

Bromley, B. C., Press, W. H., Lin, H., & Kirshner, R. P. 1998, ApJ, 505, 25

Cen, R., & Ostriker, J. P. 1998, preprint (astro-ph/9809370)

Colless, M. 1998, preprint (astro-ph/9804079)

Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. G. 1996, AJ. 112. 839

Davis, M., & Huchra, J. 1982, ApJ, 254, 437

Efstathiou, G., Ellis, R. S., & Peterson, B. S. 1988, MNRAS, 232, 431

Ellis, R. S., Colless, M., Broadhurst, T., Heyl, J., & Glazebrook, K. 1996, MNRAS, 280, 235

Folkes, S., Ronen, S., Price, I., Lahav, O., Colless, M., Maddox, S., Deeley, K., Glazebrook, K., Bland-Hawthorn, J., Cannon, R., Cole, S., Collins, C., Couch, W., Driver, S., Dalton, G., Efstathiou, G., Ellis, R., Frenk, C., Kaiser, N., Lewis, I., Lumsden, S., Peacock, J., Peterson, B., Sutherland, W., & Taylor, K. 1999, MNRAS, 308, 459

Hogg, D. W., Cohen, J., Blandford, R., & Pahre, M. A. 1998, ApJ504, 622

Kauffmann, G., Colberg, J. M., Diaferio, A., & White S. D. M. 1999, MNRAS, 303, 188

Kennicutt, R. C. 1998, ARA&A, 36, 189

Kochanek, C. S., Pahre, M., & Falco, E. E. 2000, in preparation

Leitherer *et al.* 1996, PASP, 108, 996

Lin, H., Kirshner, R. P., Shectman, S. A., Landy, S. D., Oemler, A., Tucker, D. L., & Schechter, P. L. 1996, ApJ, 464, 60

Loveday, J., Tresse, L., & Maddox, S. 1999, MNRAS, 310, 281

Pearce, F. R., Jenkins, A., Frenk, C. S., Colberg, J. M., White, S. D. M., Thomas, P. A., Couchman, H. M. P., Peacock, J. A., & Efstathiou, G. 1999, ApJ, 521, L99

Sandage, A., Tammann, G. A., & Yahil, A. 1979, ApJ, 232, 352

Schechter, P. 1976, ApJ, 203, 297

Shectman, S. A., Landy, S. D., Oemler, A., Tucker, D. L., Lin, H., Kirshner, R. P., & Schechter, P. L. 1996, ApJ, 470, 172

Small, T. A., Ma, C.-P., Sargent, W. L. W., & Hamilton, D. 1997, ApJ, 487, 512

Somerville, R. S., Lemson, G., Sigad, Y., Dekel, A., Kauffmann, G., & White, S. D. M. 1999, submitted to MNRAS, preprint (astro-ph/9912073)

York, D., *et al.* (2000), submitted to AJ

Zucca, E., Zamorani, G., Vettolani, G., Cappi, A., Merighi, R., Mignoli, M., Stirpe, G. M., MacGillivray, H., Collins, C., Balkowski, C., Cayatte, V., Maurogordato, S., Proust, D., Chincarini, G., Guzzo, L., Maccagni, D., Scaramella, R., Blanchard, A., & Ramella, M. 1997, A&A, 326, 477

This preprint was prepared with the AAS LaTeX macros v5.0.

Table 1. Modified Schechter Fit to LCRS Galaxies

	M_*	α	W_0 ($\mathring{A}$)	σ_{W}	A
	-20.32 ± 0.01	-0.91 ± 0.02	10.14 ± 0.03	0.77 ± 0.01	-0.47 ± 0.01
M_*	1.00	0.39	-0.69	0.16	-0.25
α	0.39	1.00	-0.73	0.28	-0.32
W_0	-0.69	-0.73	1.00	-0.34	0.11
σ_W	0.16	0.28	-0.34	1.00	-0.45
A	-0.25	-0.32	0.11	-0.45	1.00

Note. — Parameters of the modified Schechter function given in Equation (4) and correlation matrix between the parameters. The first line of the table gives the values of the parameters and their errors. The bottom section of the table gives the correlation matrix. Normalization is $\phi_* = 1.34 \pm 0.03$ ($\times 10^{-2}$) Mpc $^{-3}$. The errors and the correlation matrix were calculated using 200 Monte Carlo simulations. The fraction of realizations which had worse fits to the model than did the data was about $P_{\mathrm{worse}} = 0.47$, indicating that the model is consistent with the data.

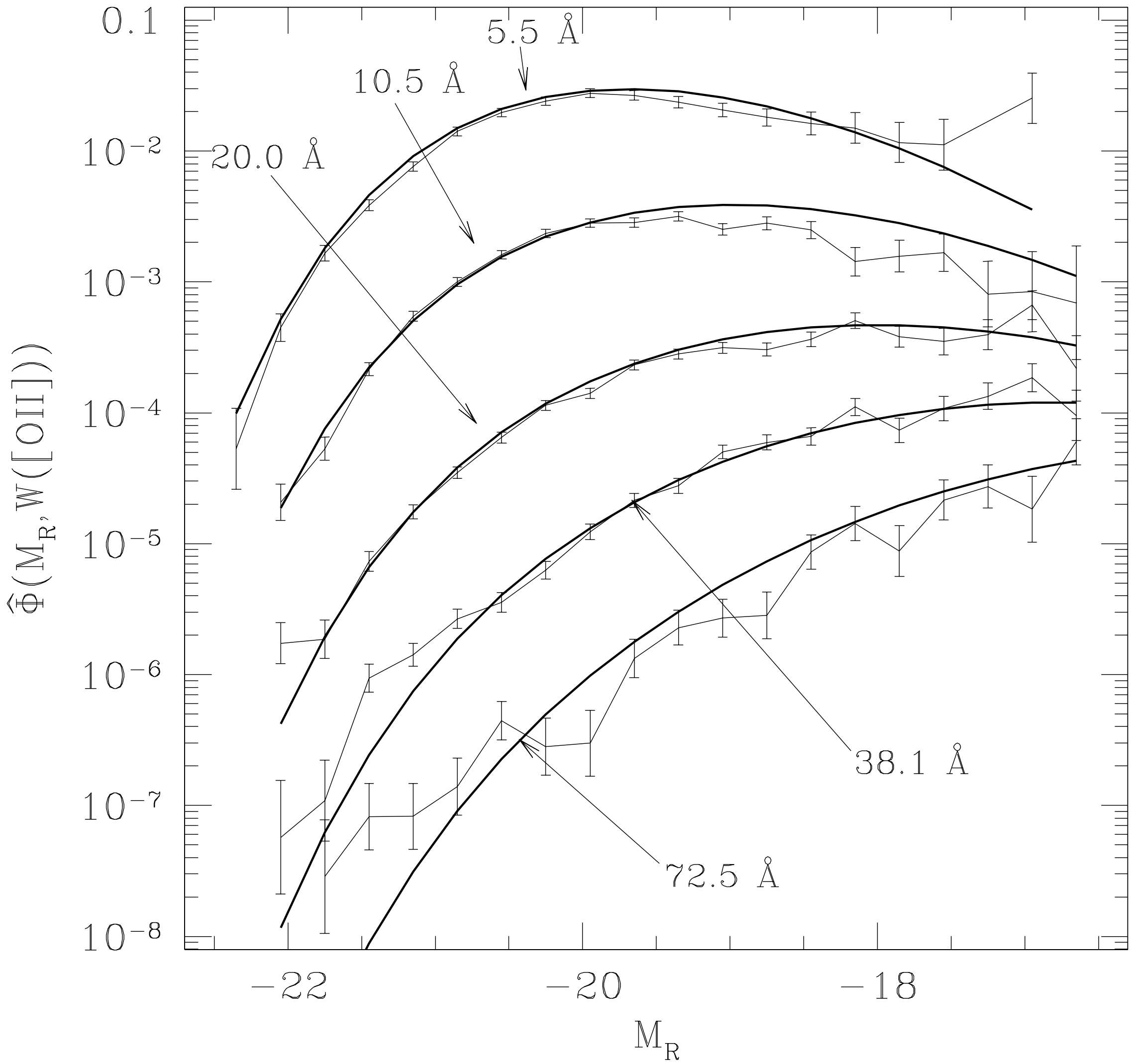

Fig. 1.— Joint distribution of luminosity and [OII] equivalent width for the approximately 8,500 LCRS galaxies (in the N112 and S112 fields) for which we have measured equivalent widths in the range 4–100 $\AA$. Curves with error bars represent the results of a two-dimensional non-parametric fit based on the method of Efstathiou, Ellis, & Peterson (1988). They are labeled by the central value of each logarithmically spaced bin in equivalent width. Note the characteristic differences in M_* and faint-end slope between the star-forming, high equivalent width galaxies, and the quiescent, low equivalent width galaxies. Smooth curves represent the best fit modified Schechter function of Equation (4), which appears to model the data well. Parameters of this fit as well as their error bars and covariances are given in Table 1. For the purposes of clarity, we have offset the 5.5$\AA$, 10.5$\AA$, and 20.0$\AA$ curves (for both the non-parametric and the modified Schechter fits) by 1.8, 1.0, and 0.3 dex, respectively.